Mapping Forces and Elasticity in Random Solids

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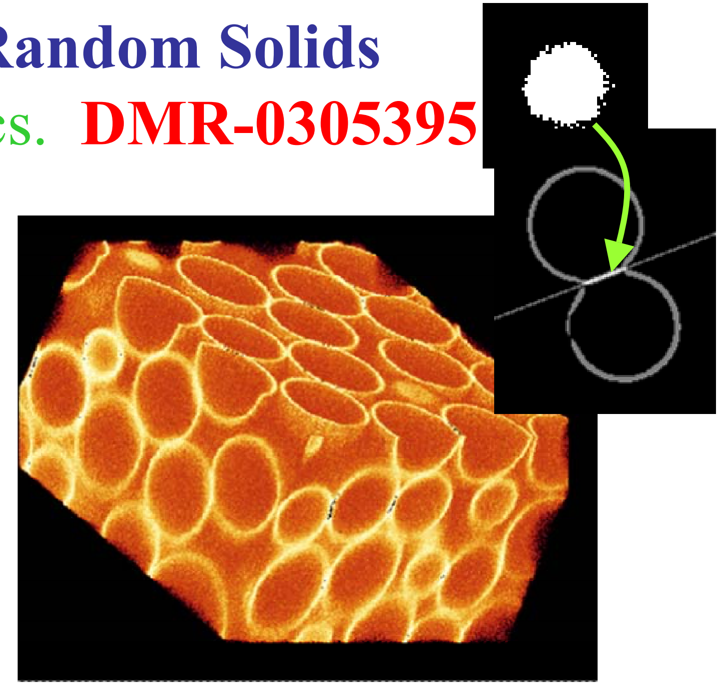
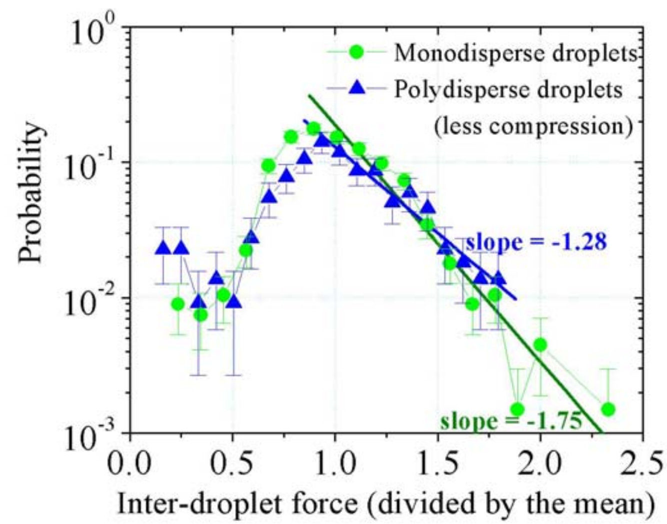
Soft random solids are common in our everyday experience, but a fundamental understanding of how their structure determines their elasticity is lacking. Although these materials are far from equilibrium and have no crystalline order, experiments have revealed a number of properties that may be universal. In sandpiles, for example, the strongest inter-particle forces may be concentrated in chain-like regions of the sample and the probability distribution of forces at the pile's surface has a peak and an approximately exponential tail (in contrast to standard elasticity).

Here we measure the spatial distribution of forces in a transparent pile of 30-µm droplets. Results to date indicate that the force distribution *in bulk* is similar to earlier measurements at the *surface* of a pile, but that the distribution changes subtly as the droplets become more compressed.



A 3D image of a droplet pile, obtained by confocal microscopy. The contact forces are obtained from the area of the circular disks where droplets touch (see inset).



Disordered solids are very common in everyday life, with examples including window glass, polymer gels, particle gels, and sand piles. Although the microscopic details of these examples differ tremendously – molecules in one case and millimeter-sized sand grains in another – there is increasing evidence that they are examples of a more general phenomenon, sometimes known as “jamming.” The challenge is that the particles or molecules are trapped in a configuration that is not the lowest-energy (equilibrium) configuration, so their behavior cannot be explained by theories that are so successfully applied to crystals, liquids and gases. In an effort to understand these materials, we create random piles of liquid droplets and measure the positions and the droplets and the magnitudes of the forces between them. In many respects, this system resembles a pile of sand grains or a solid formed by a dense packing of large polymer molecules. The latter materials, however, are either opaque or composed of particles that are too small to see. Here we use confocal optical microscopy to image the surfaces of the droplets, which are coated with a layer of bright fluorescent particles. The droplets are suspended in an immiscible fluid of the same refractive index and a three-dimensional image is obtained. By computerized image analysis, we extract the shapes of the surfaces of thousands of droplets inside the pile. The key of this technique is that two droplets form a flat circular disk where they touch; the area of this disk indicates the force between them. Our measurements of forces *inside* the random pile are consistent with earlier measurements of contact forces at the *surfaces* of such a random pile. Moving beyond the earlier experiments, however, we have found that the probability distribution of forces changes with the extent to which the pile is compressed. Continued investigations may allow us to link empirical models for infinitely rigid particles with the existing models for uniform elastic media, and to probe the effects of Brownian motion on these systems.

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Education:

One undergraduate (Debo Olaosebikan) and two graduate students (Jing Zhou and Wenfeng Kang) contributed to this work. Debo Olaosebikan worked with us this summer, visiting from Illinois Welseyan University. Jing Zhou is still a member of the PI's group and is leading these experiments. Wenfeng Kang recently departed from the PI's group.

The PI has also developed and is currently teaching a new, full-semester graduate-level course in soft condensed matter physics, the general field of this research. The class has 30 attendees.

Societal Impact:

We have developed a powerful model system, which allows us to probe the behavior of random solids. These materials are very common in everyday life, with examples including foods, powders, and polymer gels. The results are expected to lead to advances in our fundamental understanding of non-equilibrium systems in general.

The students involved in this project receive a comprehensive training in optics, computer analysis and condensed matter physics, suitable for jobs in industry or academia.